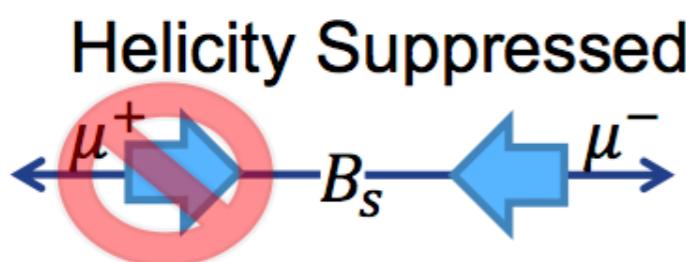
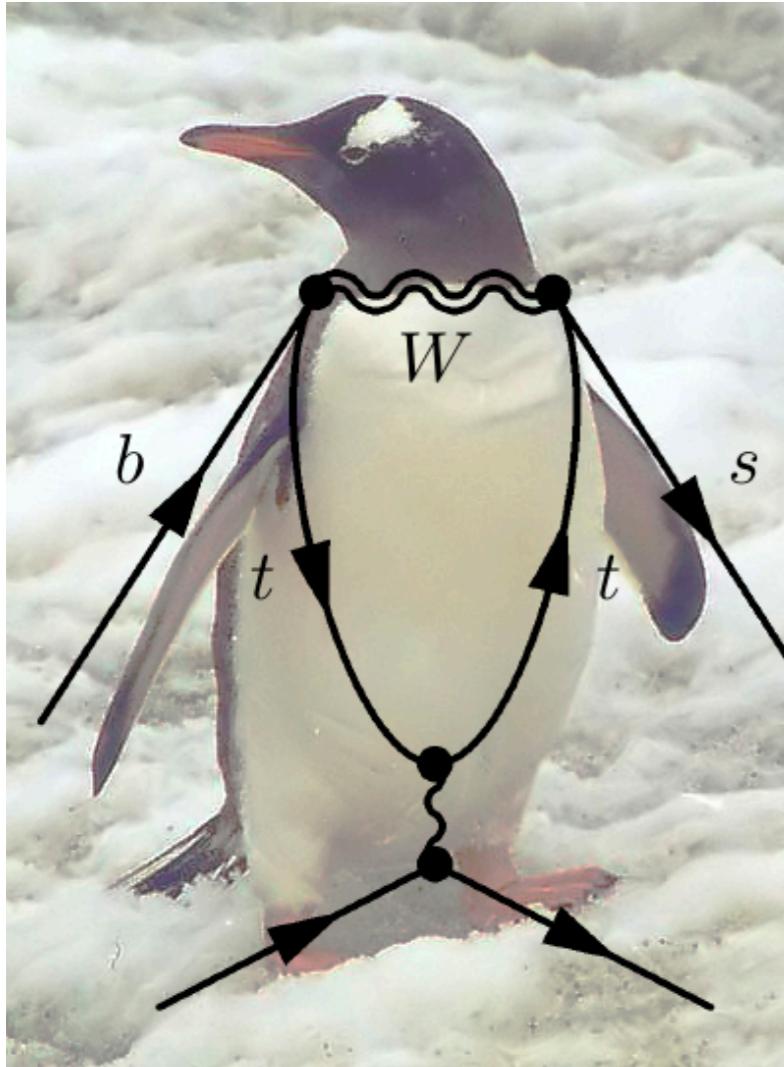


Measurements of $B_{(s)} \rightarrow \mu\mu$ decays

Dmytro Kovalskyi for the CMS Collaboration

Why $B_{(s)} \rightarrow \mu\mu$?



- Rare $b \rightarrow s \ell \ell$ process in SM (10^{-9})
 - Sensitive to New Physics effects
- Theoretically clean
 - non perturbative contributions are in $B_{(s)}$ decay constant
 - well known from Lattice QCD
- Anomalies in rare B decays
 - 3.1σ LFU violation in $R(K)$
 - $2-3\sigma$ discrepancies in branching fraction and angular observables

Analysis Strategy



$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = \mathcal{B}(B^+ \rightarrow J/\psi K^+) \times \frac{N_{B_s^0 \rightarrow \mu^+ \mu^-}}{N_{B^+ \rightarrow J/\psi K^+}} \times \frac{\epsilon_{B^+ \rightarrow J/\psi K^+}}{\epsilon_{B_s^0 \rightarrow \mu^+ \mu^-}} \times \frac{f_u}{f_s}$$

or $\left\{ = \mathcal{B}(B_s^0 \rightarrow J/\psi \phi) \times \frac{N_{B_s^0 \rightarrow \mu^+ \mu^-}}{N_{B_s^0 \rightarrow J/\psi \phi}} \times \frac{\epsilon_{B_s^0 \rightarrow J/\psi \phi}}{\epsilon_{B_s^0 \rightarrow \mu^+ \mu^-}} \right\}$

$$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = \mathcal{B}(B^+ \rightarrow J/\psi K^+) \times \frac{N_{B^0 \rightarrow \mu^+ \mu^-}}{N_{B^+ \rightarrow J/\psi K^+}} \times \frac{\epsilon_{B^+ \rightarrow J/\psi K^+}}{\epsilon_{B^0 \rightarrow \mu^+ \mu^-}} \times \frac{f_u}{f_d}$$

*external
B production
fraction ratio*

= 1

- Branching Fractions are normalized using $B \rightarrow J/\psi K$ (nominal) and $B_s \rightarrow J/\psi \phi$ (alternative) decays
 - Most systematic effects cancel in the ratio
- Measurements are performed with unbinned ML fits
 - Signal yield fit: 2D fit in mass and its uncertainty
 - Effective Lifetime: 3D fit in mass, decay time and its uncertainty

Event Selection



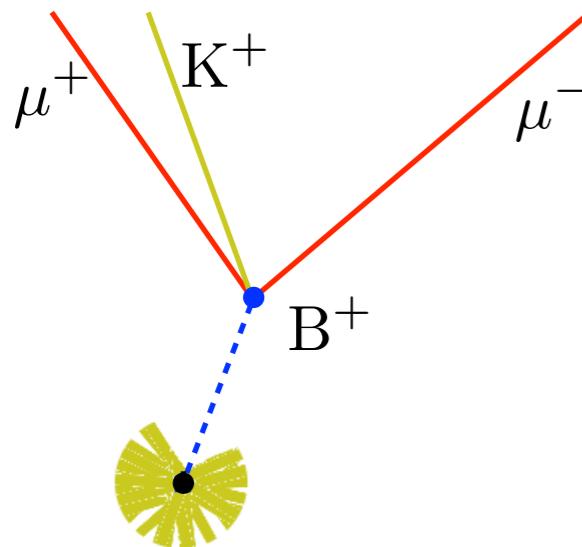
Selection	$B_s^0 \rightarrow \mu^+ \mu^-$	$B^+ \rightarrow J/\psi K^+$	$B_s^0 \rightarrow J/\psi \phi$
B candidate mass [GeV]	[4.90,5.90]	[4.90,5.90]	[4.90,5.90]
Blinding window [GeV]	[5.15,5.50]		
$p_{T\mu}$ [GeV]	> 4	> 4	> 4
$ \eta_\mu $	< 1.4	< 1.4	< 1.4
3D SV displacement significance	> 6	> 4	> 4
$p_{T\mu\mu}$ [GeV]	> 5	> 7	> 7
$\mu\mu$ SV probability	> 0.025	> 0.1	> 0.1
J/ψ candidate mass [GeV]		[2.9,3.3]	[2.9,3.3]
Kaon p_T [GeV]		> 1	> 1
Mass-constrained fit probability		> 0.025	> 0.025
2D $\mu\mu$ pointing angle [rad]		< 0.4	< 0.4
ϕ candidate mass [GeV]			[1.01, 1.03]

- Selection requirements are as loose as possible
 - Provide more data to MultiVariate Analysis (MVA)
 - Limited by trigger requirements
- Normalization channel selection is optimized to match kinematics of signal

Dominant Contributions



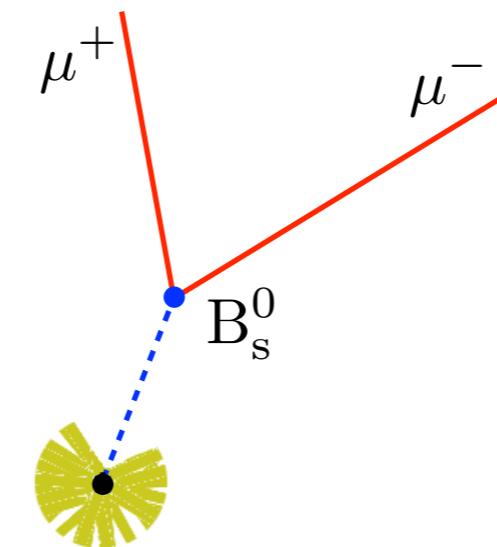
3-body and partial decays



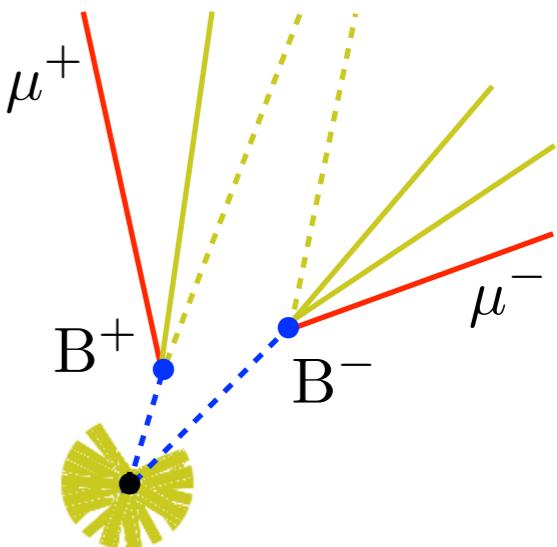
Muons from the same
B hadron



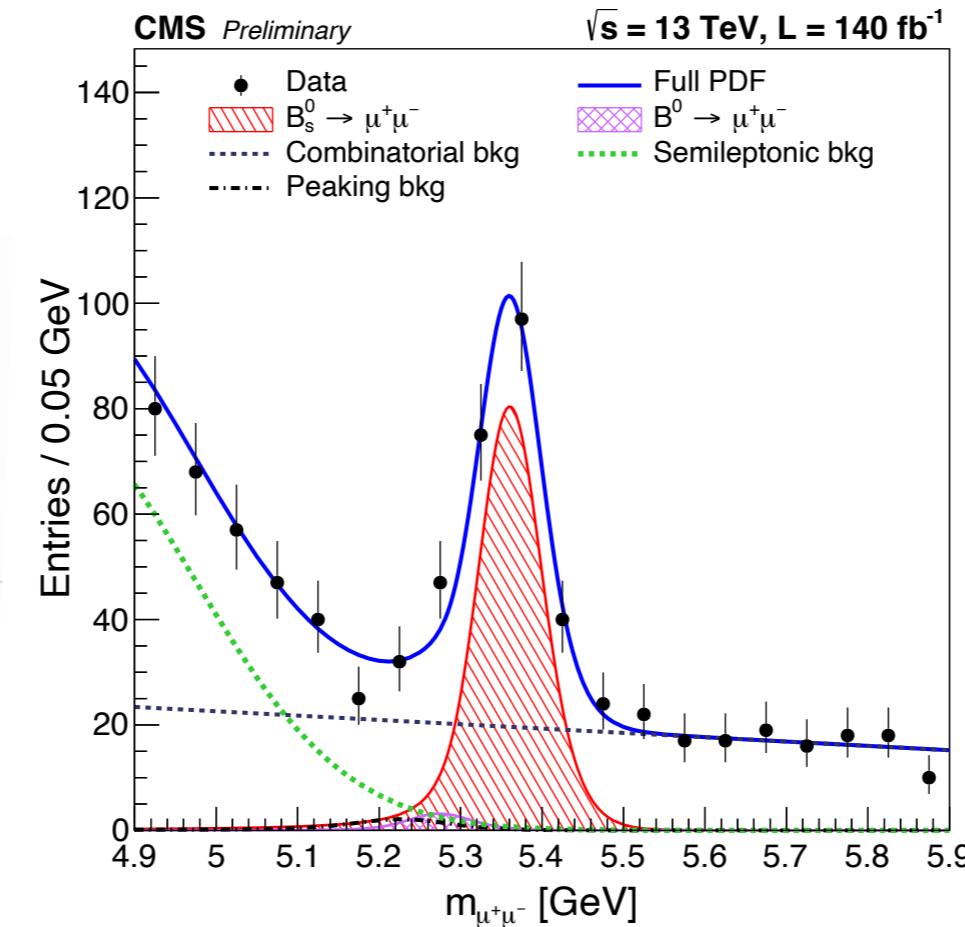
Signal $B_s \rightarrow \mu\mu$



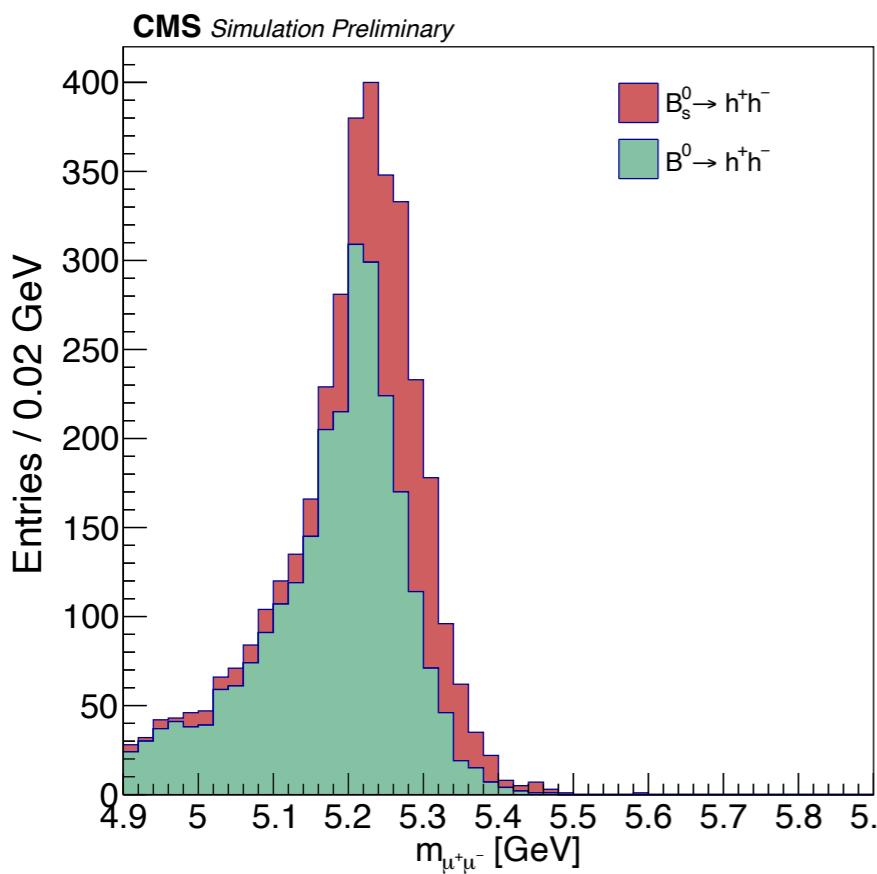
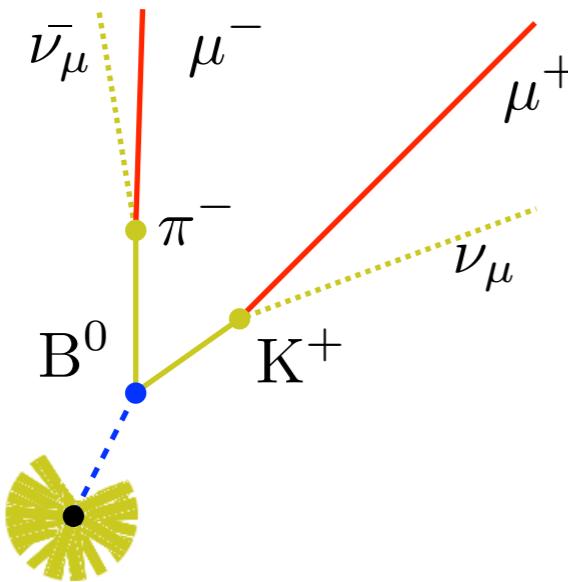
Combinatorial Background



Muons originate from
different B hadrons

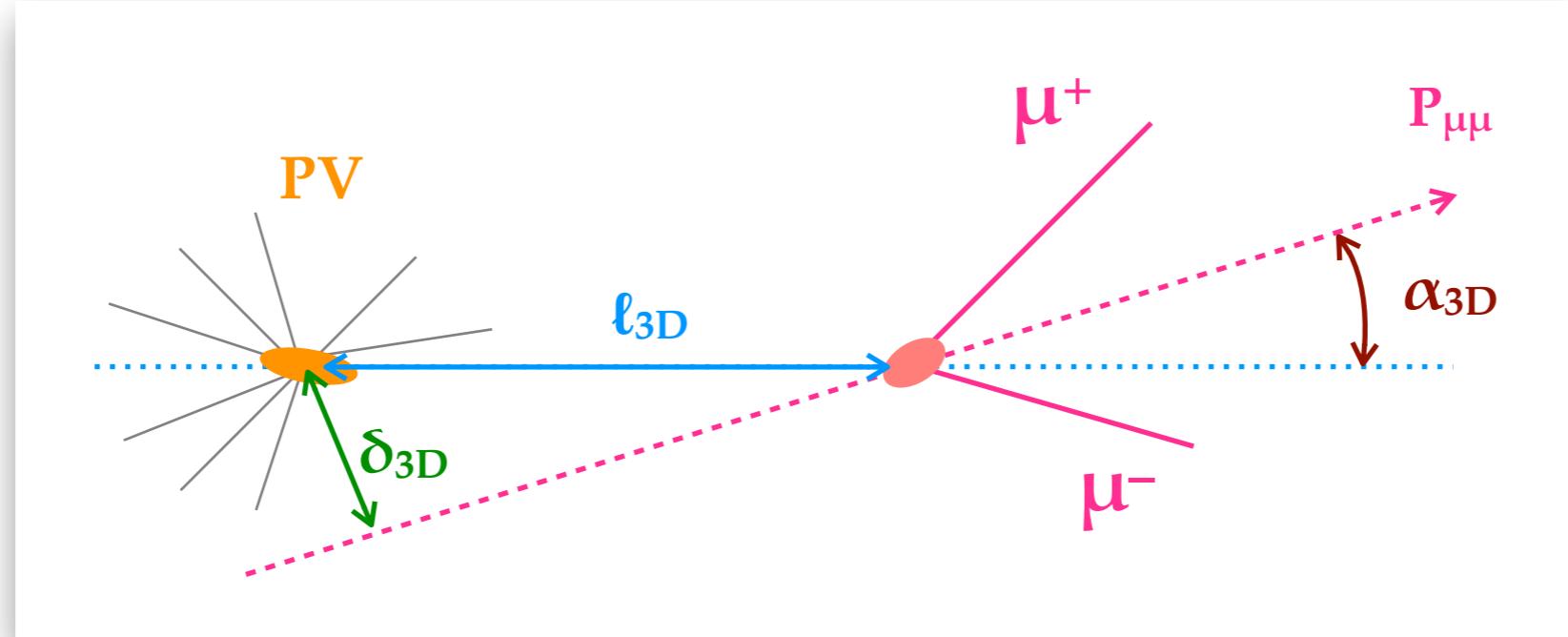


Muon Fakes



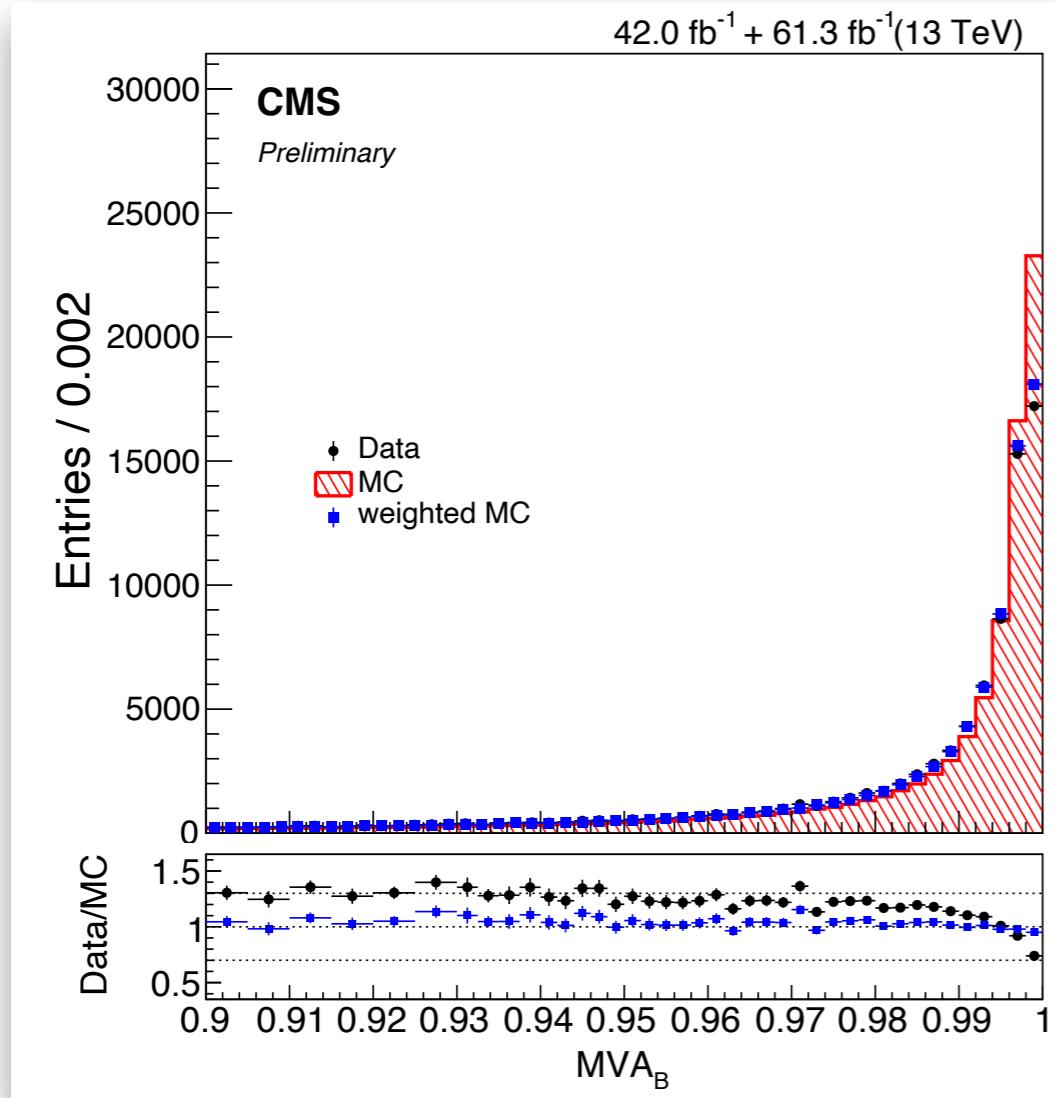
- Double muon fakes from $B \rightarrow hh$ - non-trivial background
 - Looks like signal
 - Rate is comparable to $B^0 \rightarrow \mu\mu$
 - $B \rightarrow K\pi$ and $B_s \rightarrow KK$ are dominant contribution
- Primary source of fakes
 - Pion and kaon decays in flight to muon and neutrino
 - Other contributions are negligible and easy to reject
- Used MVA based muon identification
 - Detect minor imperfections in the muon candidate trajectory
 - Factor of 2-3 better rejection of fakes than the standard muon selection
 - Kaon decays are easier to reject
- Fake rates are measured in $K_s \rightarrow \pi\pi$ and $\phi \rightarrow KK$ control samples
 - Simulated reasonably well: ~25% systematic per hadron

Multivariate Analysis



- New multivariate analysis (MVA_B) used to suppress the dominant backgrounds
 - Trained with signal MC and mass sideband data with the XGBoost package (advanced gradient boosting algorithm)
- Most discriminating variables
 - Pointing angles: α_{2D} , α_{3D}
 - Impact parameter and its significance: δ_{3D} , $\delta_{3D}/\sigma(\delta_{3D})$
 - Flight length and its significance: $\ell_{3D}/\sigma(\ell_{3D})$
 - Isolation for B candidate and muons
 - Dimuon vertex quality

MVA_B Simulation



- Use $B \rightarrow J/\psi K$ events to model $B \rightarrow \mu\mu$ decays in Data and MC
 - Additional selection requirements
 - Kaon $P_T < 1.5 \text{ GeV}$
 - Rescaled flight length significance
- Data/MC correction factors
 - Ratio method: efficiency ratio between weighted data/MC
 - XGBoost: train a XGBoost classifier to reweight MC to match to the data

Method	MVA_B>0.9			MVA_B>0.99		
	2016	2017	2018	2016	2017	2018
Ratio	1.011 ± 0.013	0.939 ± 0.007	0.903 ± 0.008	1.058 ± 0.019	0.891 ± 0.008	0.885 ± 0.010
XGBoost	0.991 ± 0.008	0.949 ± 0.003	0.917 ± 0.002	1.008 ± 0.011	0.905 ± 0.004	0.908 ± 0.002

BF Systematics



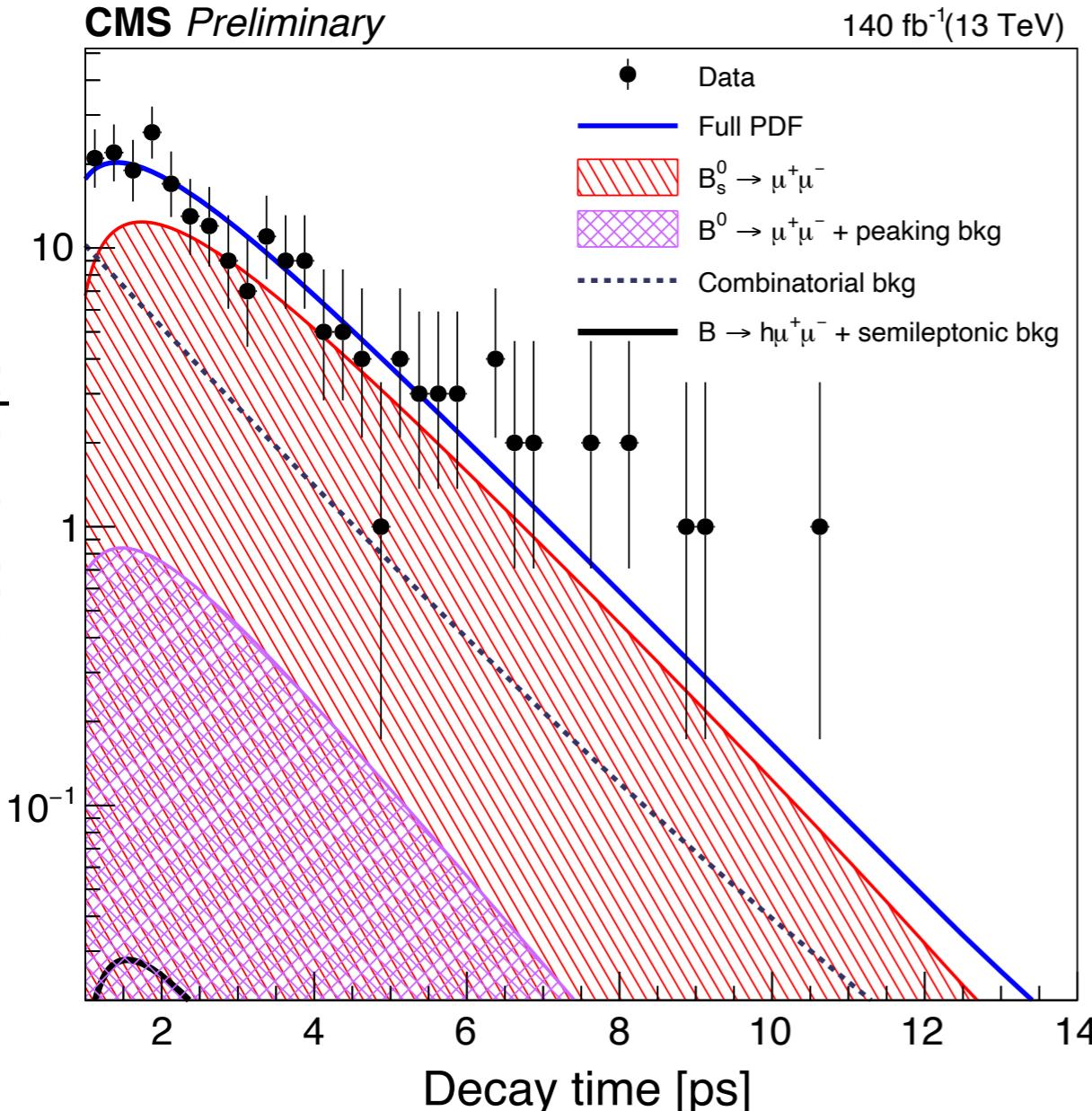
Effect	$\text{BF}(B_s \rightarrow \mu^+ \mu^-)$	$\text{BF}(B^0 \rightarrow \mu^+ \mu^-)$
Trigger efficiency	2–4%	
Pileup	1%	
Vertex quality	1%	
MVA _B correction	2–3%	
Tracking efficiency	2.3%	
J/ ψ K ⁺ shape	1%	
Fit bias	2.2%	4.5%
f_s/f_u ratio	3.5%	-

- Signal efficiency is correlated with the lifetime
 - Branching Fractions are measured assuming the SM value
 - For alternative lifetime hypothesis scale BF using the following expression
- $$\alpha_{\text{BF}} = 1.577 - 0.358 \tau$$
- τ is in ps

Effective Lifetime Measurement

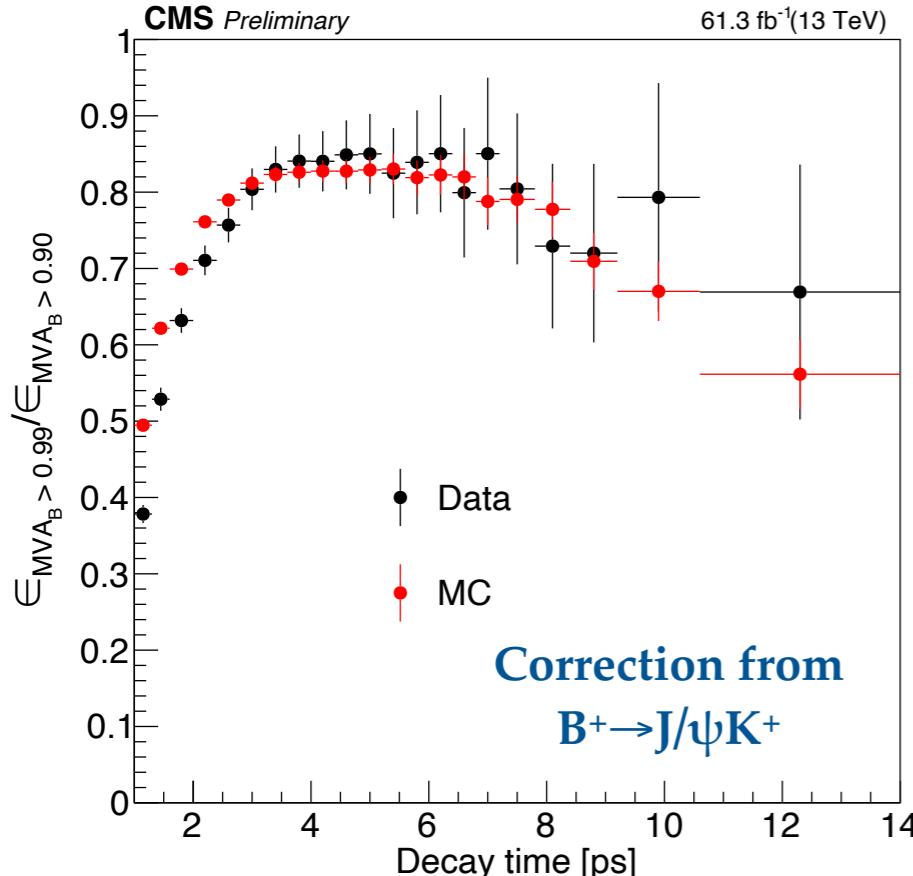


CMS Preliminary



- In the absence of CP violation only the heavy B_s state decays into dimuon
 - Different composition of states may be allowed by New Physics.
- Efficiency correction
 - Decay time efficiency derived from MC
 - Corrected by $B^+ \rightarrow J/\Psi K^+$ data to mitigate the bias from tight MVA_B requirement.
 - The residual bias and the difference between $B_s \rightarrow \mu\mu$ and $B^+ \rightarrow J/\Psi K^+$ are considered as a systematic uncertainty.

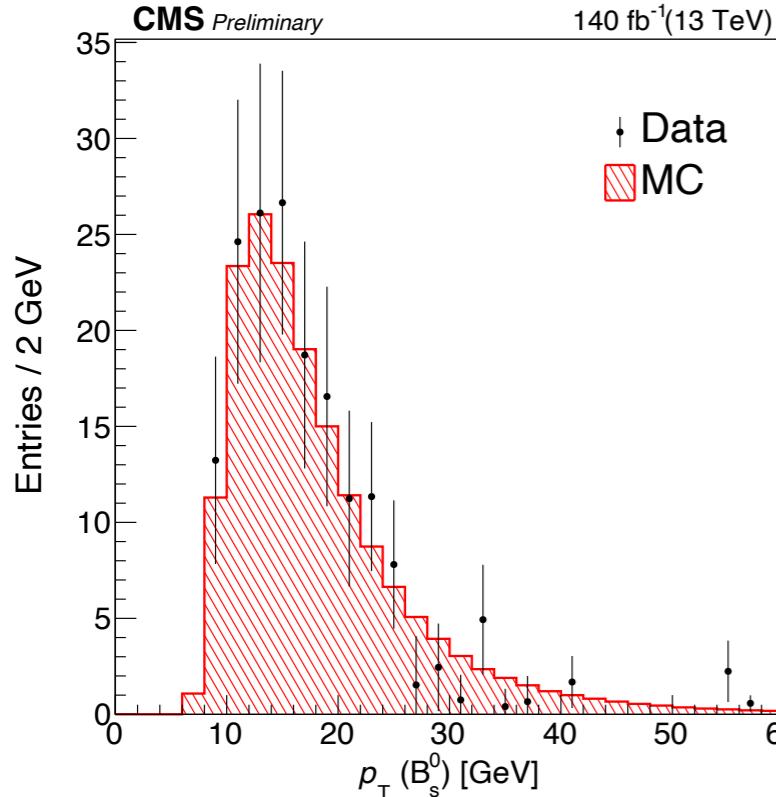
Lifetime Systematics



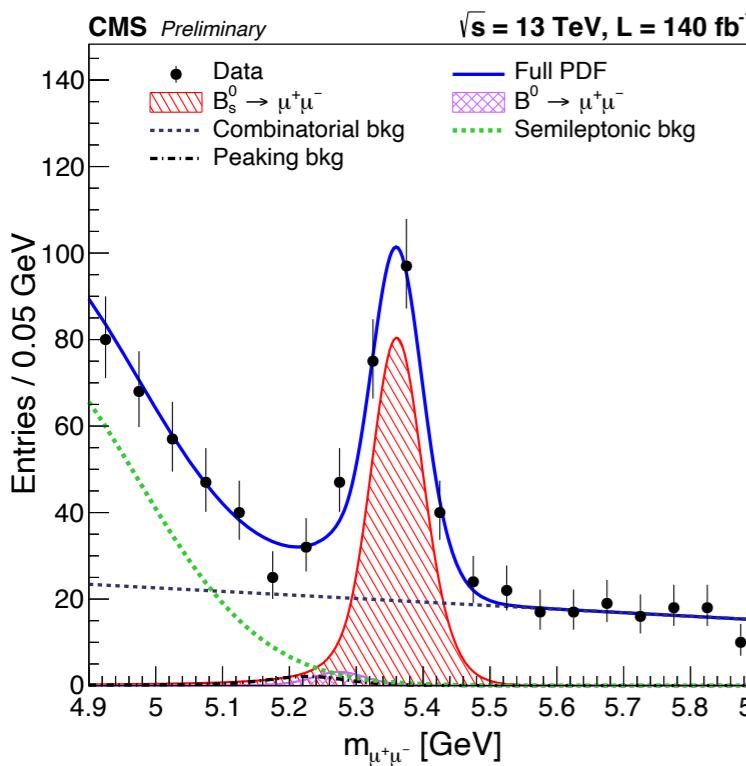
Effect	2016BF	2016GH	2017	2018
Efficiency modeling		0.01 ps		
Scanning over different gen lifetime sample		0.01 ps		
Decay time mis-modeling	0.10 ps	0.06 ps	0.02 ps	0.02 ps
Lifetime bias	0.04 ps	0.04 ps	0.05 ps	0.04 ps
Total	0.11 ps	0.07 ps	0.05 ps	0.04 ps

- Dominant systematics comes from a strong correlation between MVA_B and decay time, which are hard to model well
 - Corrections can be derived in data and uncertainty is mostly limited by the size of the control sample

fs/fu ratio in BF fit



$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = \mathcal{B}(B^+ \rightarrow J/\psi K^+) \frac{N_{B_s^0 \rightarrow \mu^+ \mu^-}}{N_{B^+ \rightarrow J/\psi K^+}} \frac{\epsilon_{B^+ \rightarrow J/\psi K^+} f_u}{\epsilon_{B_s^0 \rightarrow \mu^+ \mu^-} f_s},$$



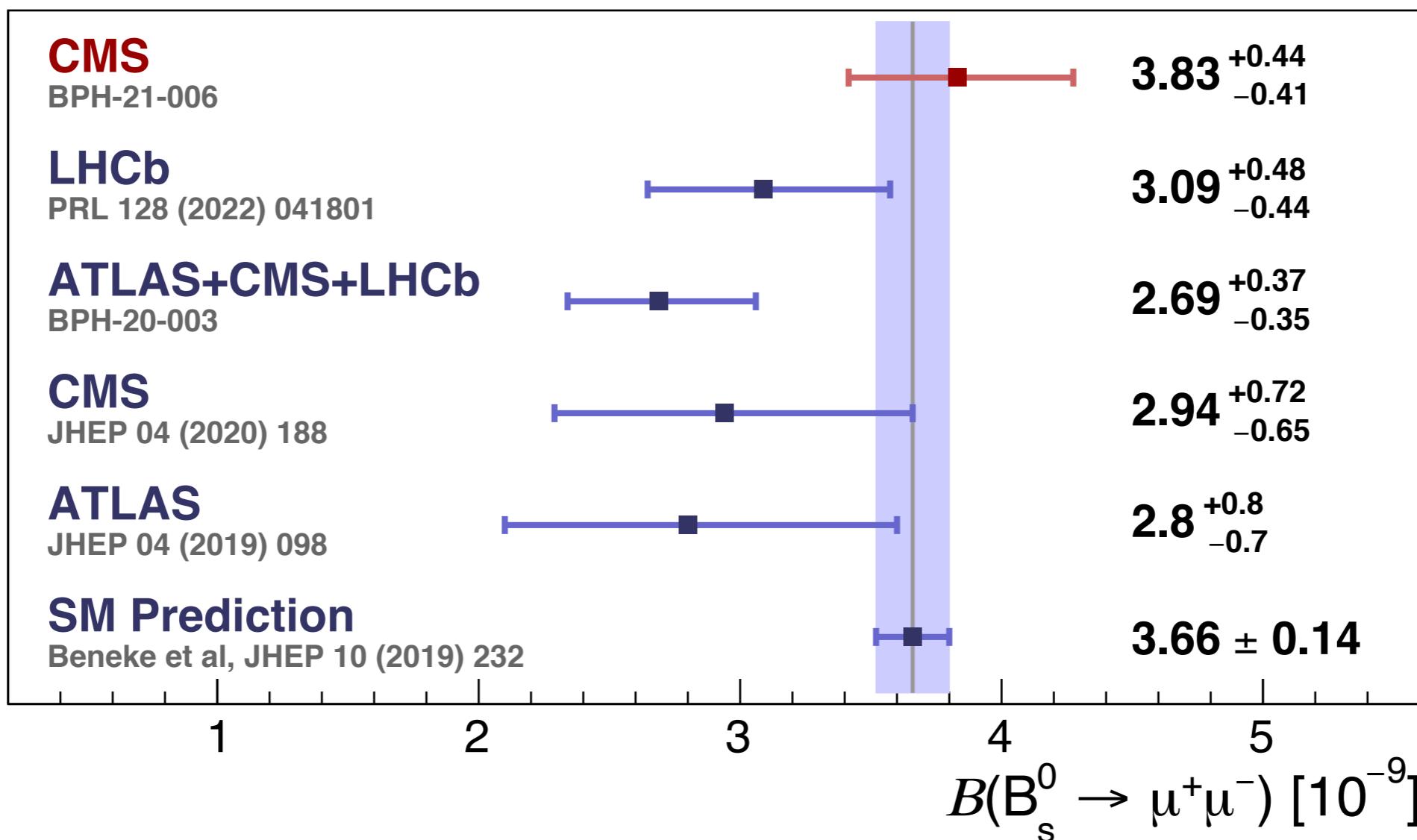
- $f_s/f_u = 0.231 \pm 0.008$
 - Based on P_T -dependent results from LHCb
 - PRD 104 (2021) 032005
 - Integrate with the effective P_T distribution
 - Previous measurement used 0.252 ± 0.032
- Resulting BF can be rescaled:
 - One can use a different f_s/f_u value
 - Treated as an external uncertainty
 - not as a constrained nuisance parameter

$B_s \rightarrow \mu\mu$ BF Result



$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = [3.83^{+0.38}_{-0.36} \text{ (stat)}^{+0.19}_{-0.16} \text{ (syst)}^{+0.14}_{-0.13} (f_s/f_u)] \times 10^{-9}$$

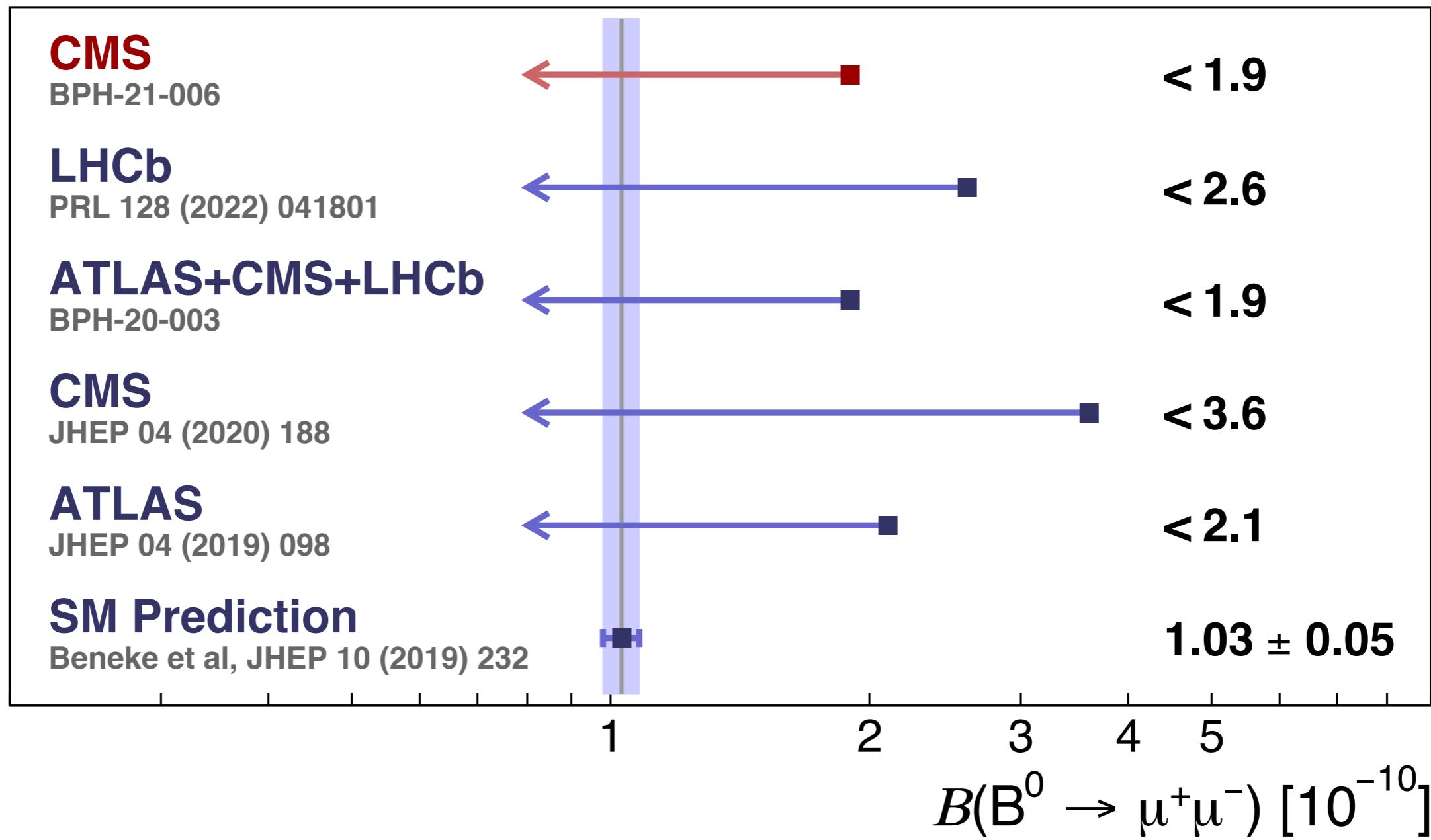
Alternative using $B_s \rightarrow J/\psi \phi$: $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = [3.95^{+0.39}_{-0.37} \text{ (stat)}^{+0.27}_{-0.22} \text{ (syst)}^{+0.21}_{-0.19} \text{ (BF)}] \times 10^{-9}$



$B^0 \rightarrow \mu^+ \mu^-$ Search



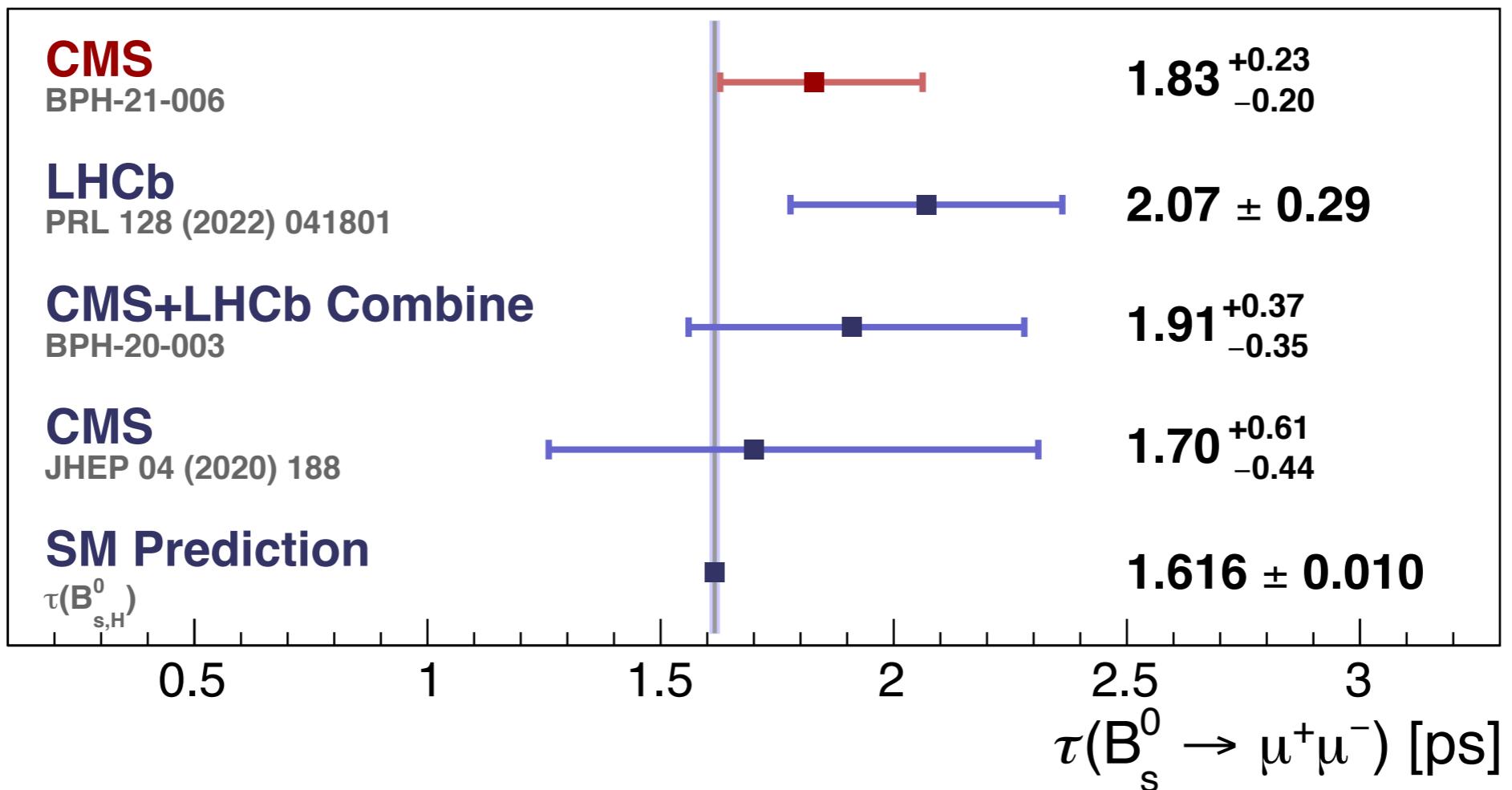
$$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = [0.37^{+0.75}_{-0.67} \text{ (stat)} ^{+0.08}_{-0.09} \text{ (syst)}] \times 10^{-10}$$



Effective Lifetime



$$\tau = 1.83^{+0.23}_{-0.20} \text{ (stat)}^{+0.04}_{-0.04} \text{ (syst) ps}$$

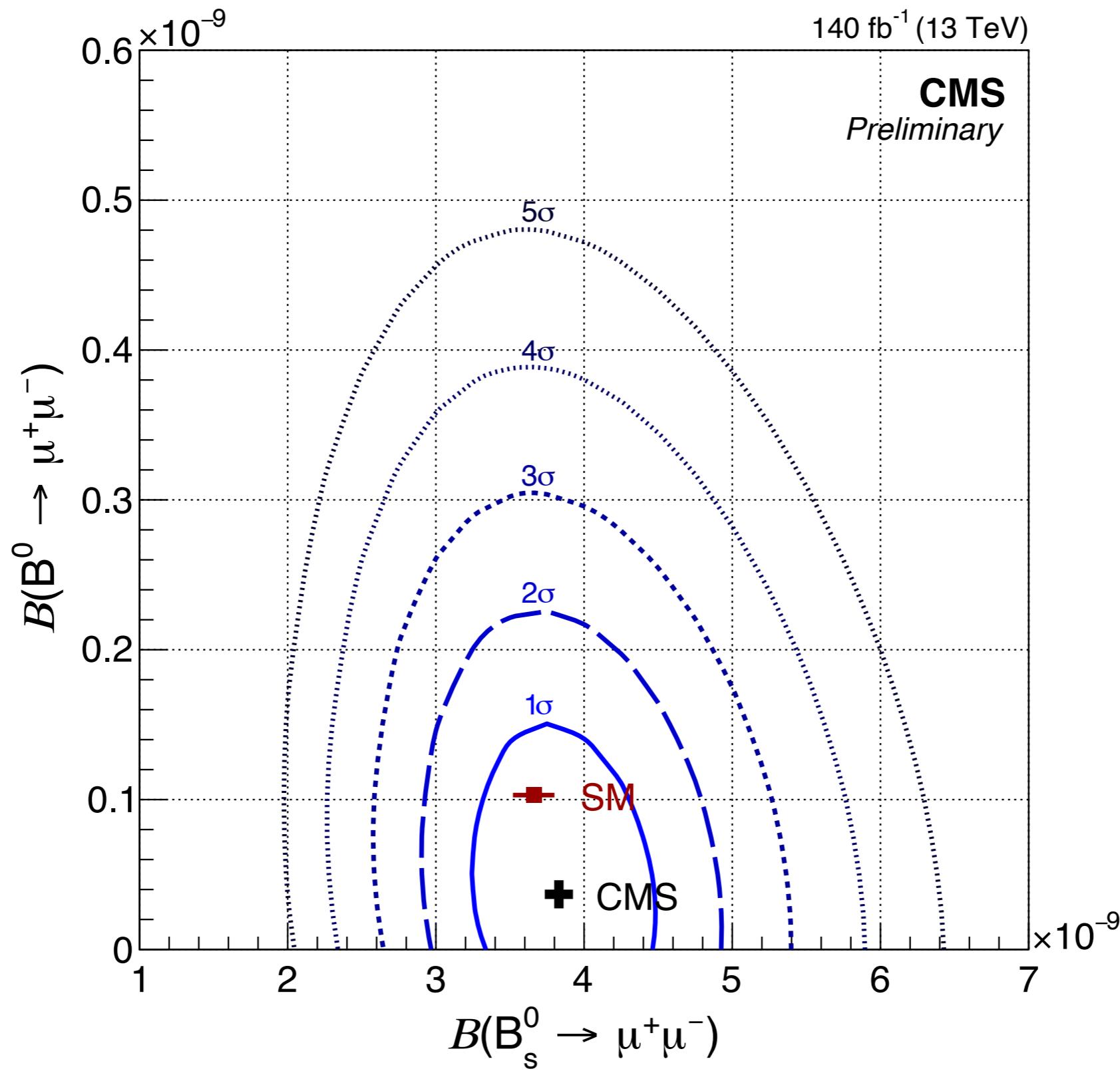


Summary

- Studies of rare $B_{(s)} \rightarrow \mu^+ \mu^-$ decays provides a unique tool to explore and understand rare B decay anomalies
 - Theoretically clean
 - Sensitive to the same processes
- CMS finalized analysis of 140 fb^{-1} data collected during LHC Run-2
 - All results are consistent with SM predictions
- Relative uncertainty on $\text{BF}(B_s \rightarrow \mu^+ \mu^-)$ has been reduced to 11%
 - The best single measurement to date
- Statistical uncertainty dominates
 - Good perspectives for further improvements with upcoming Run-3 data
- A conference note will be available shortly at
 - [https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/
BPH-21-006/index.html](https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/BPH-21-006/index.html)

Back Up

Contour Plot



Event Display

